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J. H. Kinney, Q. C. Johnson, J. M. Brase,
M. C. Nichols, R. Nusshardt, and U. Bonse

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A HIGH-RESOLUTION CT SYSTEM FOR ELEMENTAL MAPPING*

John H. Kinney, Quintin C. Johnson, and James M. Brase
Lawrence Livermore National Laboratory, Livermore, California, U.S.A.

Monte C. Nichols
Sandia National Laboratory, Livermore, California, U.S.A.

Ulrich Bonse and Rudolf Nusshardt
University of Dortmund, Dortmund, West Germany

ABSTRACT

We have tested the performance of a low-temperature CCD camera for application in computed tomography (CT) on beamline II-3 at the Stanford Synchrotron Radiation Laboratory (SSRL). In our present system, transmitted x-rays are converted to visible light on a phosphor-coated optical face plate. This light illuminates a thermoelectrically cooled CCD, which is operated as a charge counting device. By modulating the energy of the x-ray beam, we can obtain elemental and chemical-state information about the reconstructed voxels. Presently, the resolution is about 50 microns, and is to a large extent controlled by the quality of the phosphor. We report on the spatial resolution and chemical sensitivity of the system. Applications to materials and biological sciences will be discussed.

INTRODUCTION

The increased availability of synchrotron radiation, which is noted for high brightness and low divergence, makes possible the development of high-resolution computed tomography (HRCT) for biological and materials studies. Furthermore, the fact that these sources can produce high fluxes of nearly monochromatic radiation leads to the exciting possibility of performing nondestructive elemental[1,2] and chemical-state[3] mapping in small samples. This is done by using digital subtraction techniques across the x-ray absorption edge (elemental analysis) or the differences in the x-ray absorption fine structure (chemical-state analysis).

HRCT, aside from requiring a high intensity source, requires a high-resolution, high dynamic-range detector. Previous attempts at HRCT have used scanning pinhole collimator techniques,[4] or linear photodiode arrays[5] to achieve high resolution. A major drawback to the pinhole collimator is the time that it takes to perform HRCT measurements, since all of the transmitted x-ray projections must be measured separately. The advantages to this approach, however, are that the resolution is determined by the collimator, and that conventional detector technology can be used.

Linear photodiode arrays have problems, also. First, though several x-ray projections can be measured simultaneously, a large amount of information is lost because only a single slice can be examined at one time. Second, photodiode arrays have inherently greater noise problems than CCDs, which limits the sensitivity of the measurements.[6]

In this paper, we will discuss the performance of a CCD array detector for use in a HRCT system designed for elemental mapping in small samples. The experimental apparatus, which was tested at SSRL, will be described, and the performance of the CCD array will be discussed. Finally, we will show the results of a HRCT experiment where we used the CCD array camera to demonstrate elemental mapping. This

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paper will not describe the reconstruction algorithms necessary to perform HRCT. This is discussed extensively elsewhere.[7,8]

EXPERIMENTAL ASSEMBLY

Figure 1 shows the experimental apparatus for performing HRCT. The x-ray beam from the SPEAR storage ring is made nearly monochromatic ($\Delta E/E \sim 10^{-4}$) with a double crystal monochromator. This beam passes through a sample that is mounted to a precision rotating stage. The transmitted beam is incident on a phosphor screen (P46 phosphor), which illuminates a thermoelectrically cooled CCD array. At present, the CCD is held under high-vacuum to minimize the effects of condensation at low temperatures (-60°C).

The CCD camera is operated in a charge-integrating mode, and exposure times range from a fraction of a second to a minute depending on the x-ray beam intensity. The data from the camera are read off as a 14-bit data string into a MicroVax II minicomputer. Image-processing software and CT-reconstruction algorithms are resident on the mini for subsequent data processing. Presently, the maximum size of the reconstructed volume is 4 mm in the vertical by 8 mm in diameter.

CCD PERFORMANCE

The performance criteria we chose to use for a HRCT detector are (1) spatial resolution, (2) linearity, (3) dynamic range (full well capacity/RMS noise) and (4) efficiency. For HCRT, it is desirable to have a spatial resolving power in excess of 10 line pairs/mm, since present generation CT scanners approach this value.[9] Linearity is mandatory in all CT systems regardless of spatial resolution. Any nonlinearities lead to ring artifacts in the reconstructed image. The dynamic range, defined here as the full well capacity of the CCD divided by the RMS noise (read noise), determines to some extent whether signal averaging can be used to

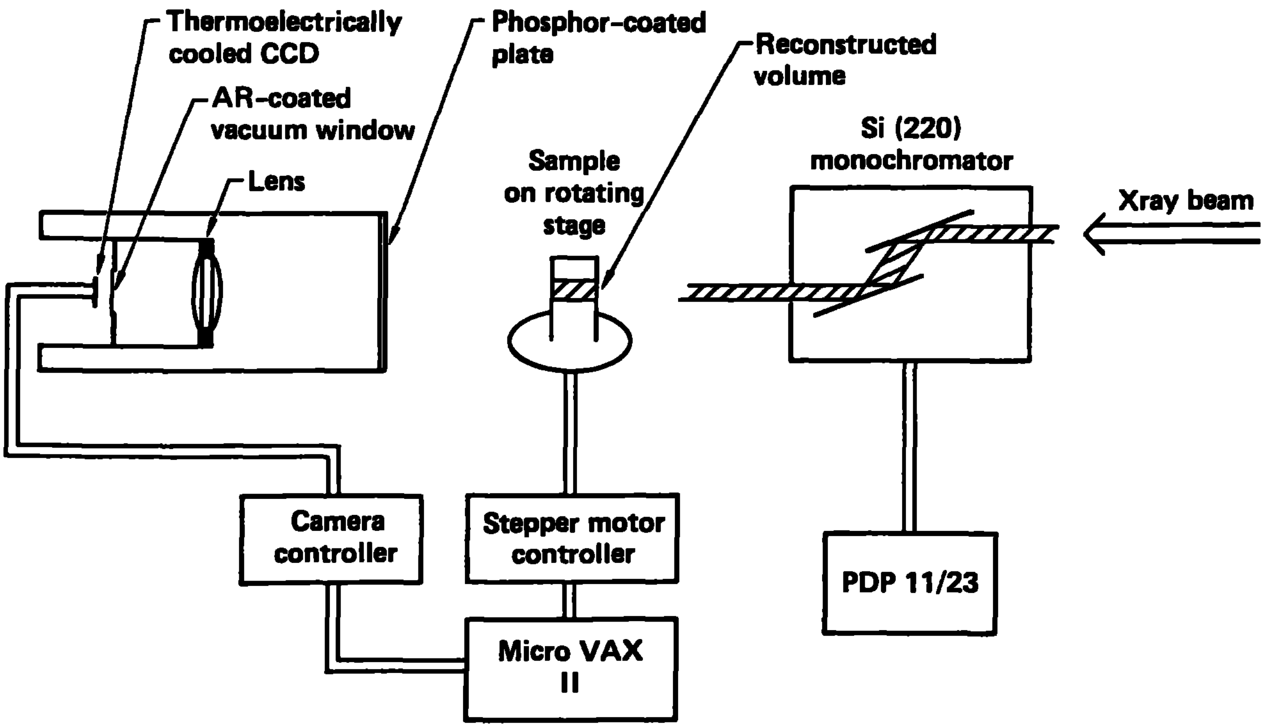

Fig. 1. Experimental apparatus for performing high-resolution computed tomography (HRCT).

increase signal-to-noise. The dynamic range also determines the thickness/density of an object that can be contrasted. Finally, the detector efficiency determines the contrast sensitivity, which can be obtained with a given photon fluence. The higher the efficiency, the less counting time is required to reach a given signal-to-noise (in the ideal case where S/N is determined by photon statistics).

We will present a detailed evaluation of the CCD camera at the conference. Briefly, however, the CCD had a resolving power of about 25 line pairs/mm. This can be increased greatly in future experiments by design changes. The CCD was linear over a range of exposures approaching the full well capacity. The dynamic range exceeded 10^4, and 2% of all x-rays incident on the phosphor were detected by the CCD.

One area of concern is the presence of a signal-dependent background. This was at first attributed to beam hardening and x-ray scatter off of high contrast objects. After further analysis, however, we believe this background is due to scattering of light off of imperfections in the AR coatings as well as light backscattered from the CCD surface.[10] This noise might be reduced by the addition of a fiber-optic coupling to the CCD. This modification is in progress.

PERFORMANCE

The performance of the HRCT system described above will be discussed at the conference. In a preliminary experiment designed to test the spatial resolution, as well as the chemical sensitivity of the technique, it was found that quite good elemental contrast could be achieved with concentrations less than 10% and resolution of about 50 microns. The absolute elemental sensitivity will depend on the x-ray dose and the composition of the specimen.[1] We believe that elemental concentrations as low as 10 to 100 ppm can be imaged with this technique.

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